Stability mechanism of proton and dark matter

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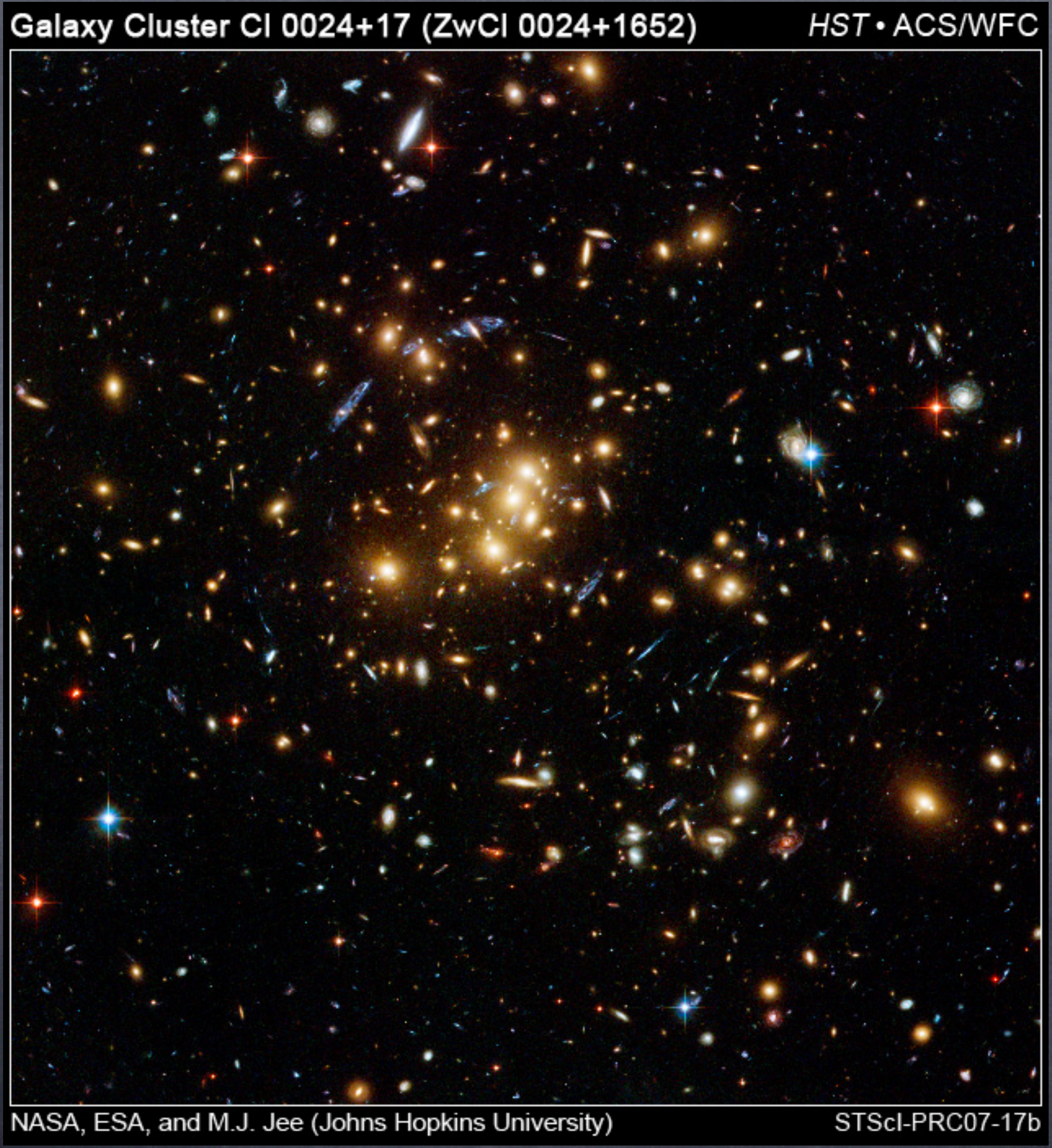
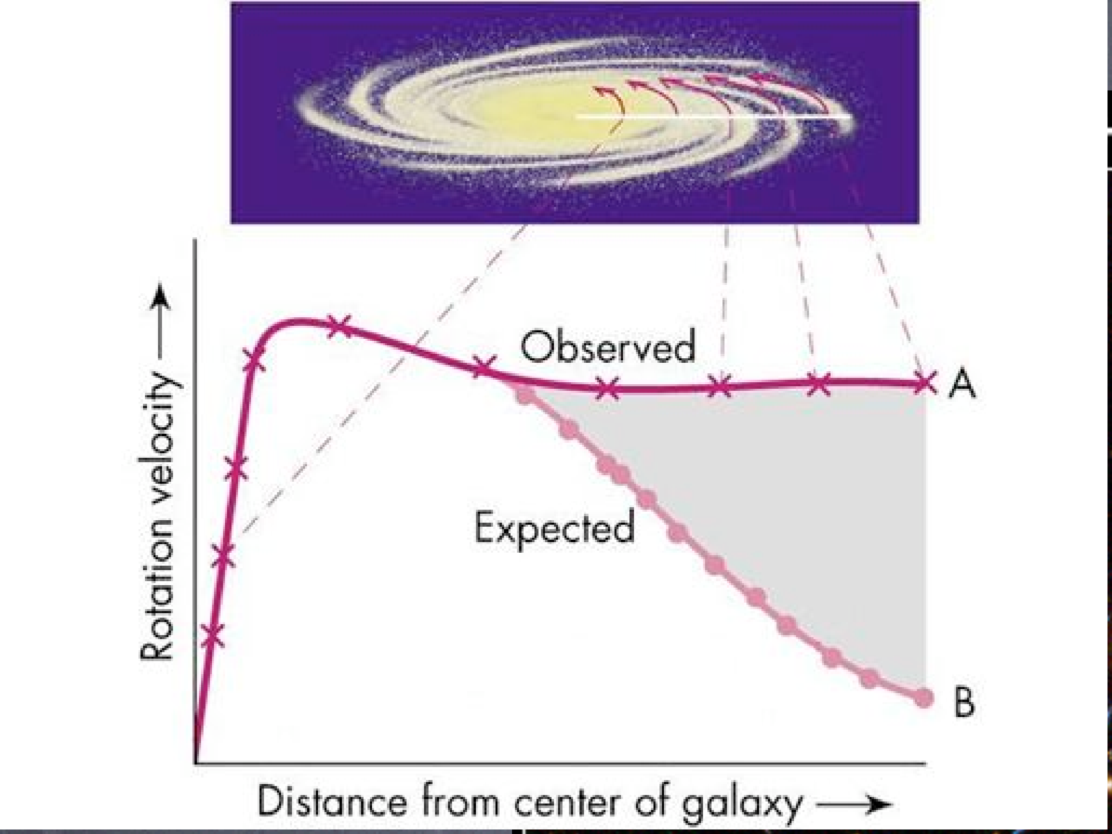
UC Riverside

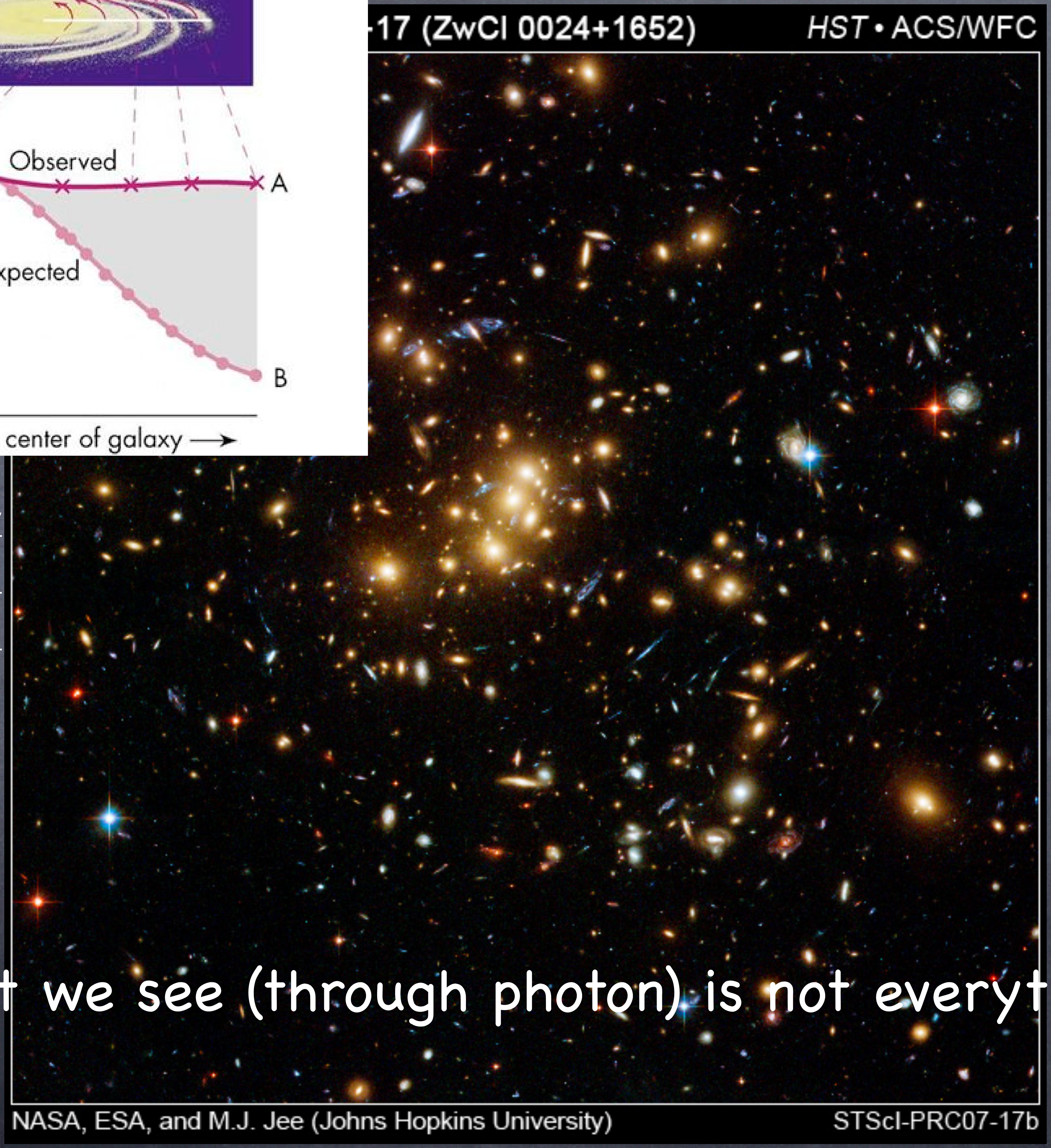
UKC 2009 (Raleigh, NC)


Galaxy Cluster Cl 0024+17 (ZwCl 0024+1652)
HST • ACS/WFC
NASA, ESA, and M.J. Jee (Johns Hopkins University)
STScI-PRC07-17b

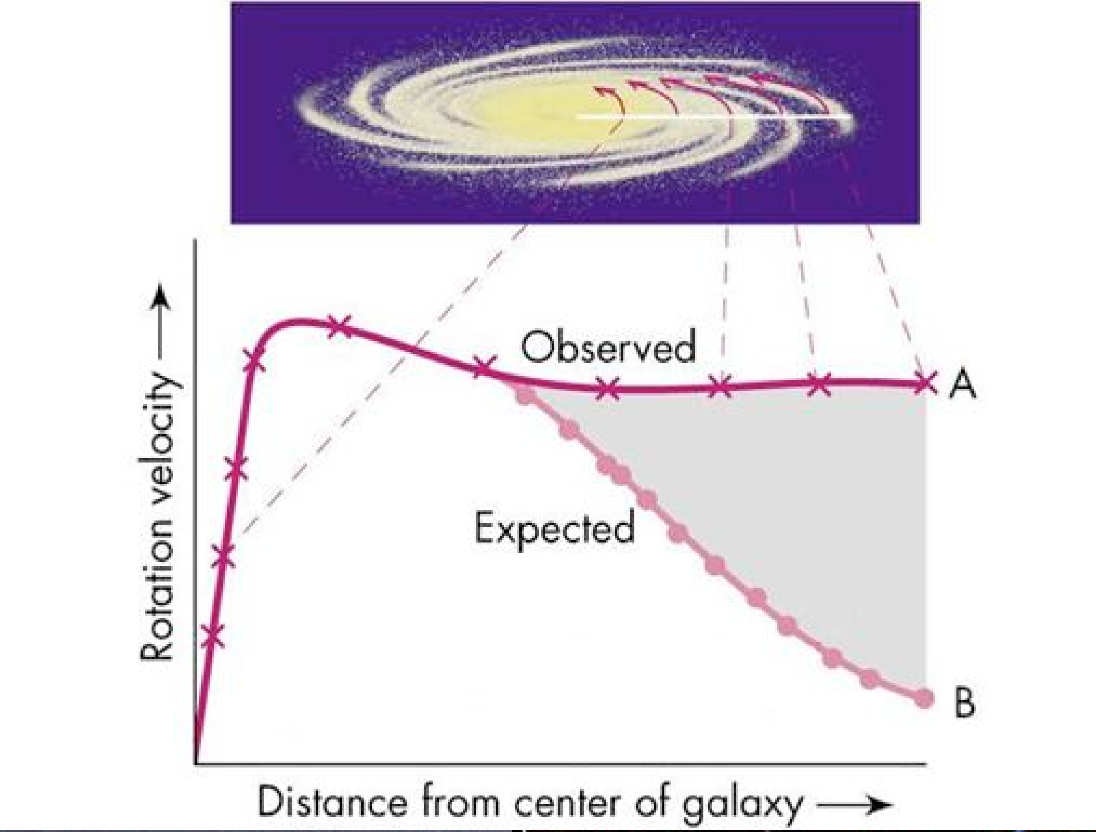


$$\frac{mv^2}{r} = G\frac{Mm}{r^2}$$

$$v(r) = \sqrt{\frac{GM(r)}{r}}$$



What we see (through photon) is not everything.



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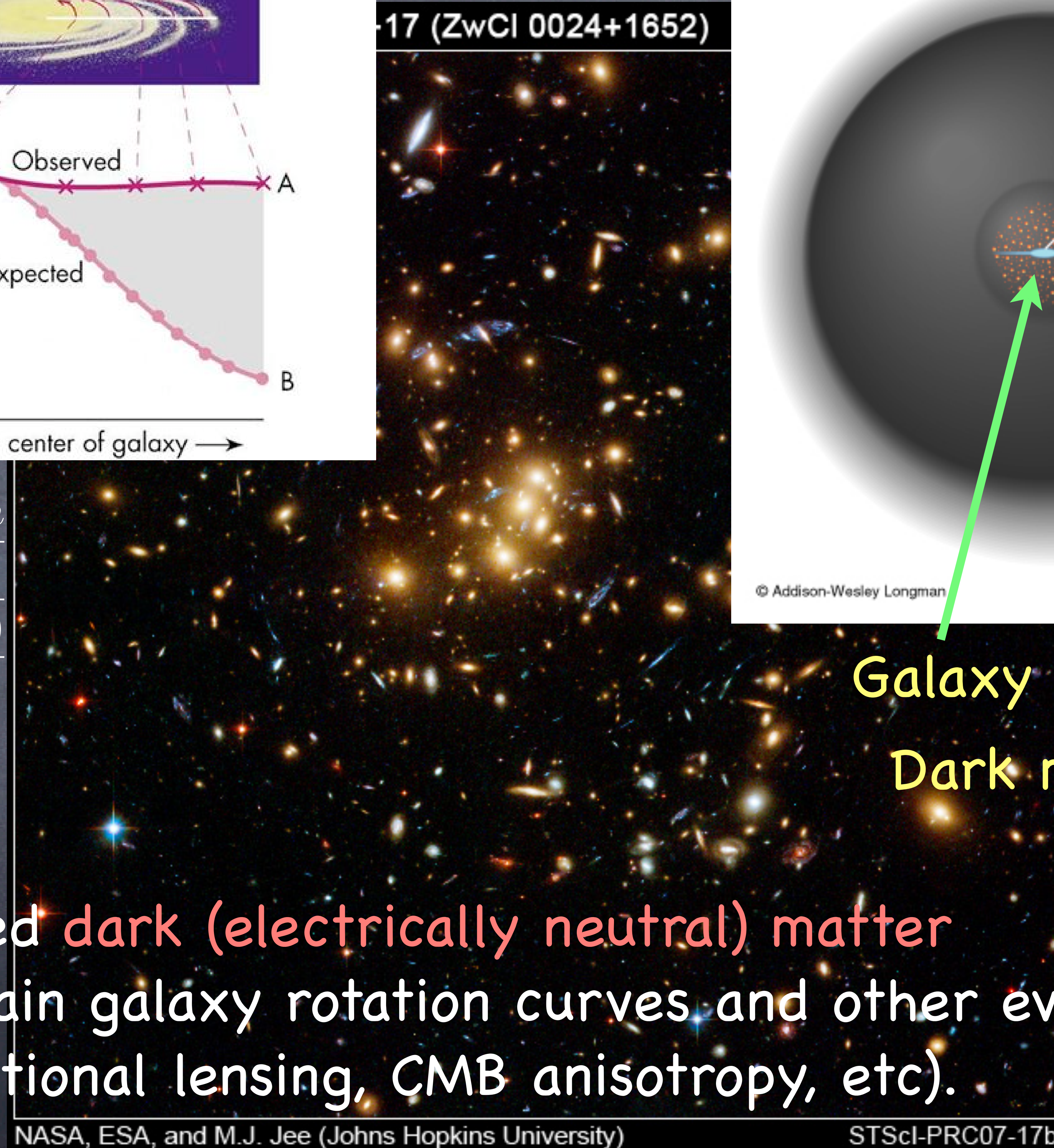

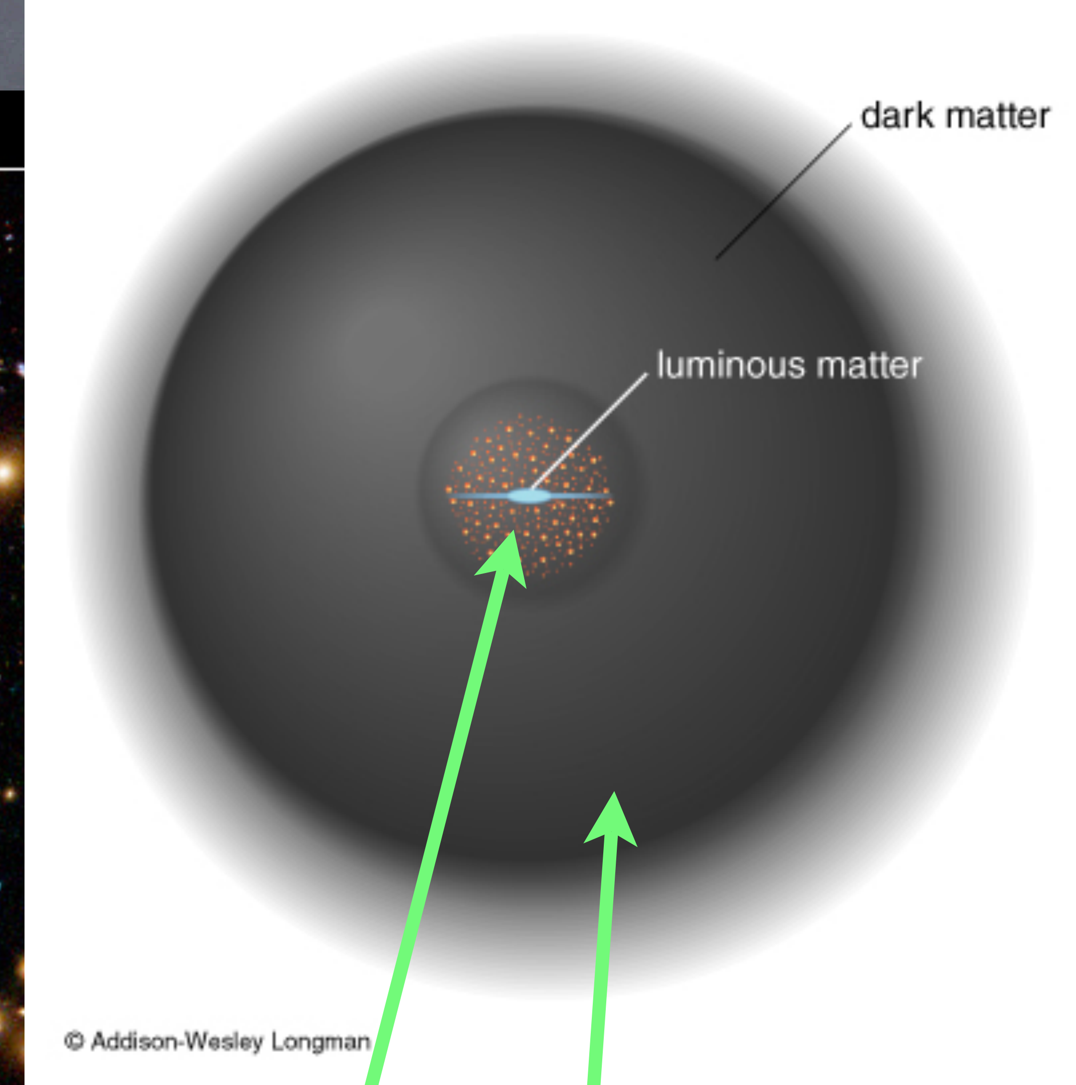

Galaxy

Dark matter halo

We need dark (electrically neutral) matter
to explain galaxy rotation curves and other evidences
(gravitational lensing, CMB anisotropy, etc).


Galaxy Cluster Cl 0024+17 (ZwCl 0024+1652)
HST • ACS/WFC
Universe = Bright world + Dark world
(proton, etc) (dark matter)
NASA, ESA, and M.J. Jee (Johns Hopkins University)
STScI-PRC07-17b

Under Supersymmetry (SUSY),
proton and dark matter candidate decay rapidly.

Observation says proton and dark matter
should be extremely long-lived.

Q: What stabilizes them?

- Popular candidate: R-parity
- Alternative: U(1)′ gauge symmetry

Outline

1. Why SUSY?

Under Supersymmetry (SUSY),
proton and dark matter candidate decay rapidly.

2. SUSY needs a companion mechanism.

Observation says proton and dark matter
should be extremely long-lived.

Q: What stabilizes them?

3. What is R-parity?

- Popular candidate: R-parity
- Alternative: U(1)′ gauge symmetry

4. What kind of U(1)′ can replace R-parity?

5. What are implications of U(1)′ for LHC?

1. Why Supersymmetry?

Higgs is special in the SM

Spin 0	"Scalar"	Higgs (H)
Spin 1/2	"Fermions"	Quarks (Q), Leptons (L)
Spin 1	"Gauge bosons"	Photon (γ), Gluon (G), W, Z

gauge group = SU(3) x SU(2) x U(1)
(All known forces except for gravity)

Higgs: the only undiscovered particle and
the only scalar (spin 0) particle.

Higgs scalar can explain the masses of the fermions and gauge bosons (otherwise, massless).

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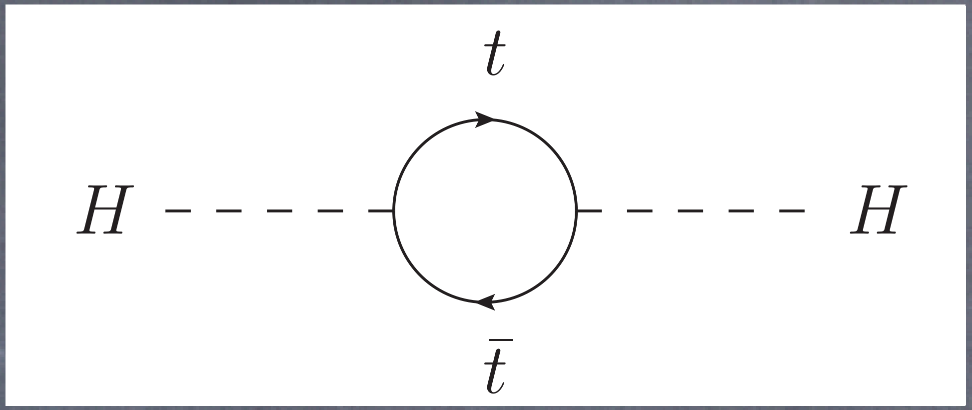
Higgs: the only undiscovered particle and
the only scalar (spin 0) part

Major discovery goal at LHC

Higgs scalar can explain the masses of the fermions and gauge bosons (otherwise, massless).

Higgs is a solution and a problem



$$\delta m_H^2(\text{top}) = -\frac{3}{8\pi^2}\lambda_t^2\Lambda^2 + \cdots$$ (Λ=cutoff scale of theory)

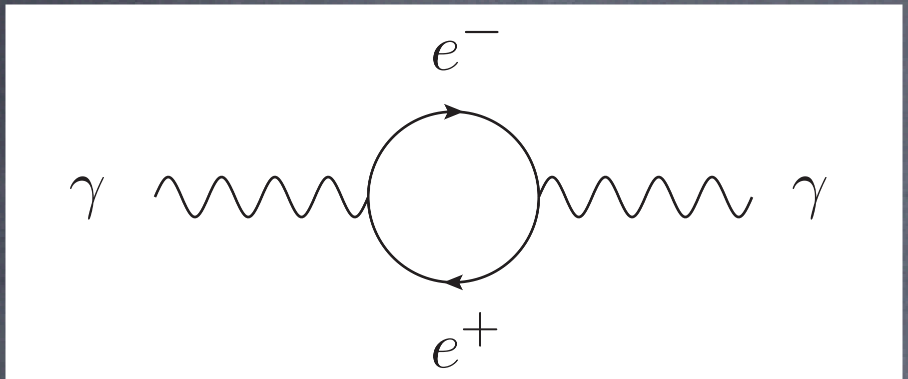
Divergence (Λ^2) in quantum correction of scalar mass^2.

If SM is valid up to gravity scale ($M_{Pl}=10^{19}$ GeV),
natural Higgs mass is about the same scale.
Physical Higgs mass should be O(100 GeV).

Something is missing in SM
-> Great motivation to look for new physics

What about other particles?

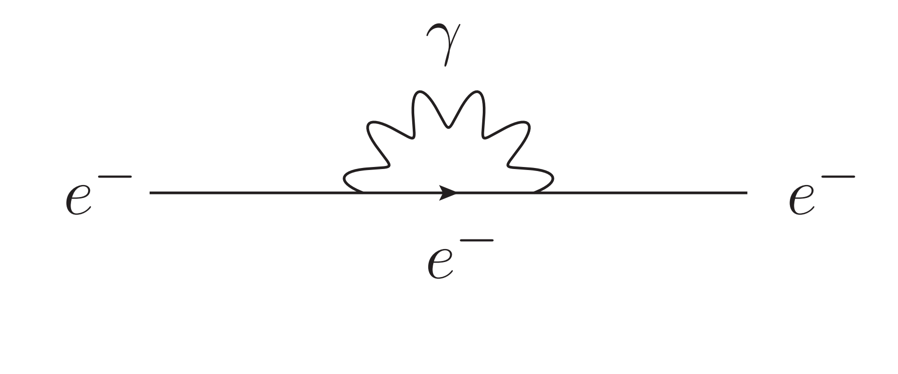
- Spin 1 particle (gauge boson):



$$\delta m_\gamma = 0$$

"Spin 1 particle mass is protected by gauge symmetry."

- Spin 1/2 particle (fermion):



$$\delta m_e \simeq \frac{2\alpha_{em}}{\pi} m_e \log \frac{\Lambda}{m_e} \simeq 0.24 m_e$$

$$(\text{for } \Lambda = M_{Pl} = 10^{19} \text{ GeV})$$

"Spin 1/2 particle mass is protected by chiral symmetry."

Look for a new symmetry to protect spin 0 particle (scalar) mass.

Supersymmetry (SUSY)

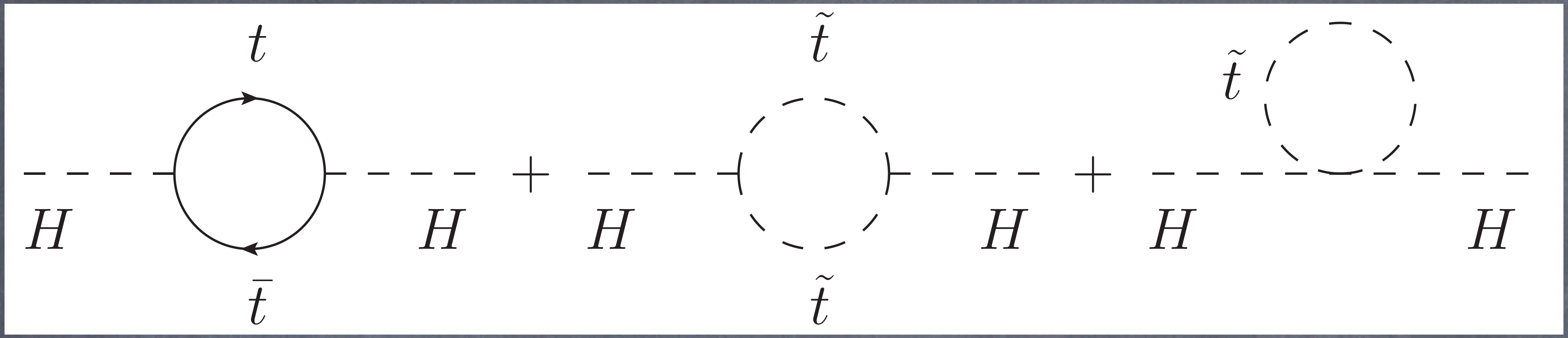
SUSY: fermion (spin 1/2) <--> boson (spin 0, 1)

SUSY predicts superpartners of different spins, which double the particle contents.

Spin 0	Higgs (H)	Spin 1/2	Higgsino ($\tilde{H}$)
Spin 1/2	Quark (Q), Lepton (L)	Spin 0	Squark ($\tilde{Q}$), Slepton ($\tilde{L}$)
Spin 1	γ, G, W, Z	Spin 1/2	$\tilde{\gamma}$, $\tilde{G}$, $\tilde{W}$, $\tilde{Z}$

[SM particles] [Superpartners]

Higgs problem motivates SUSY



$$
\begin{aligned}
\delta m_H^2(\text{top} + \text{stop}) &= \left(-\frac{3}{8\pi^2}\lambda_t^2\Lambda^2 + \cdots\right) + \left(\frac{3}{8\pi^2}\lambda_t^2\Lambda^2 + \cdots\right) \\
&= -\frac{9}{8\pi^2}\lambda_t^2 m_{\tilde{t}} \log\frac{\Lambda}{m_{\tilde{t}}} + \cdots
\end{aligned}
$$

Divergence (Λ^2) cancelled!

"Spin 0 particle (scalar) mass can be protected by supersymmetry."

SUSY in literature

Although there are other ideas ...

SPIRES database search results	
"Supersymmetry" in title	7300 papers
"Higgs" in title	8700 papers

SUSY in literature

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Another major discovery goal at LHC

Which supersymmetric SM?

- Certain: SUSY is a prevailing new physics scenario.
- Not Certain: Which supersymmetric SM?

  (distinguished by “SUSY companion symmetry”)

Predictions of the SUSY model may depend on this additional symmetry.
-> It is important to develop viable SUSY companion symmetries, and their implications.

Which supersymmetric SM?

- Certain: SUSY is a prevailing new physics scenario.
- Not Certain: Which supersymmetric SM?

  (distinguished by "SUSY companion symmetry")

Predictions of the SUSY model may depend on this additional symmetry.
-> It is important to devel ompanion symmetries, and their impl

LHC signals of Higgs & SUSY may change.

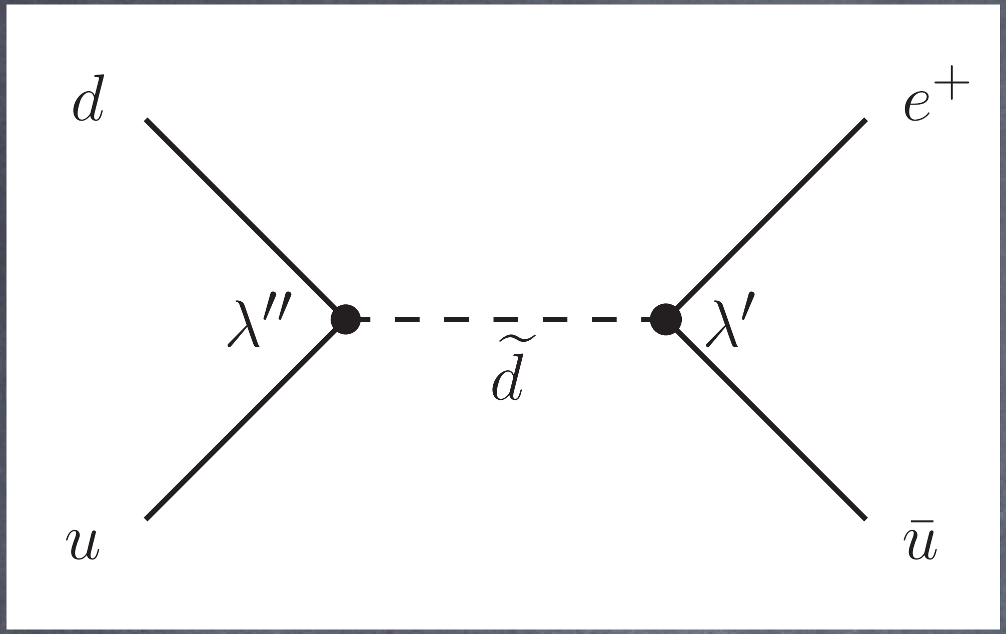
2. Why SUSY companion symmetry?

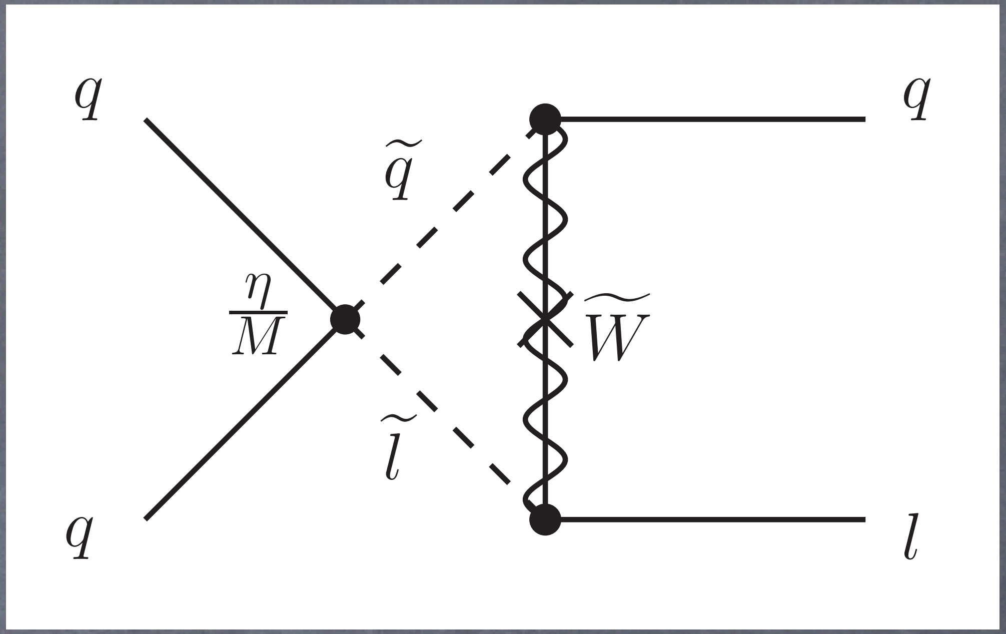
General SUSY

$$\begin{aligned} W &= \mu H_u H_d \\ &+ y_E H_d L E^c + y_D H_d Q D^c + y_U H_u Q U^c \\ &+ \lambda L L E^c + \lambda' L Q D^c + \mu' L H_u + \lambda'' U^c D^c D^c \\ &+ \frac{\eta_1}{\Lambda} QQQL + \frac{\eta_2}{\Lambda} U^c U^c D^c E^c + \cdots \end{aligned}$$

- Lepton number (L) and/or baryon number (B) violating terms at renormalizable and non-renormalizable levels:
  - one of the most general predictions of SUSY.
  - also source of problems.

Proton decay





[Dim 4 L viol. & Dim 4 B viol.]

$\lambda LLE^c + \lambda' LQD^c$ & $\lambda'' U^c D^c D^c$

[Dim 5 B&L viol.]

$$\frac{\eta_1}{\Lambda} QQQL + \frac{\eta_2}{\Lambda} U^c U^c D^c E^c$$

To satisfy proton lifetime > 10^{29} years,

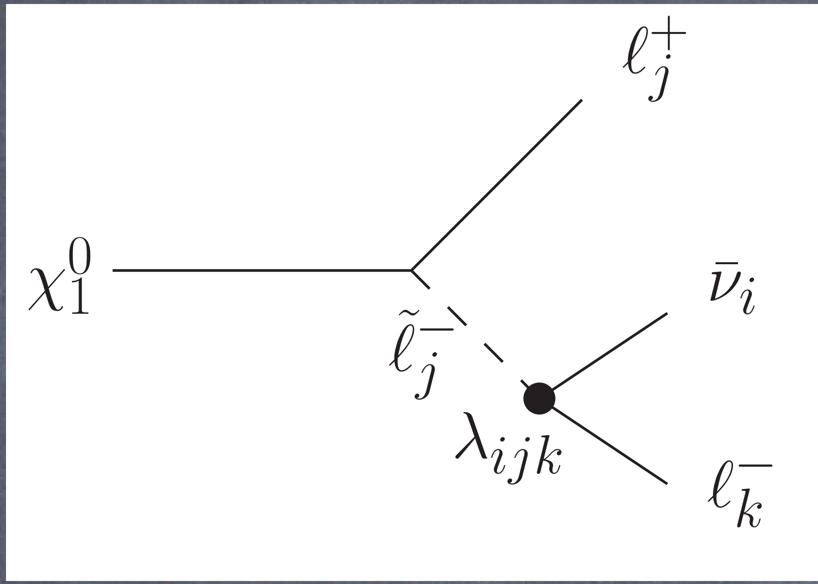
$$|\lambda_{LV} \cdot \lambda_{BV}| < 10^{-27}$$

(if one is 0, the other can be large)

$$|\eta| < 10^{-7}$$

(for $\Lambda = M_{Pl}$)

Dark matter candidate decay (lightest neutralino)



$$\Gamma = \lambda_{ijk}^2 \frac{\alpha}{128\pi^2} \frac{m_{\chi^0}^5}{m_{\tilde{f}}^4}$$

(ex: for χ~photino)

To be a viable dark matter, lifetime > Universe age (14 x 10^9 years)

$$|\lambda_{LV}|,\ |\lambda_{BV}| < 10^{-20}$$

Dark matter candidate

(to form galaxies and their clusters)

- A viable dark matter candidate should
  - be Cold (non-relativistic), Neutral, Stable.
  - explain relic density (WMAP, SDSS) : 23% of total energy density.
  - satisfy direct detection experiments limit (CDMS, XENON, KIMS, etc.).

SM: neutrino (m_ν<0.1 eV) is neutral and stable, but relativistic.

SUSY: neutralino (superpartners of neutral Higgs and gauge bosons) is neutral and heavy (therefore, cold).

-> Dark matter candidate if stable

SUSY needs a companion mechanism or symmetry.
(for stability of proton and dark matter)

3. R-parity

: Most popular SUSY companion symmetry

R-parity (superpartner parity)

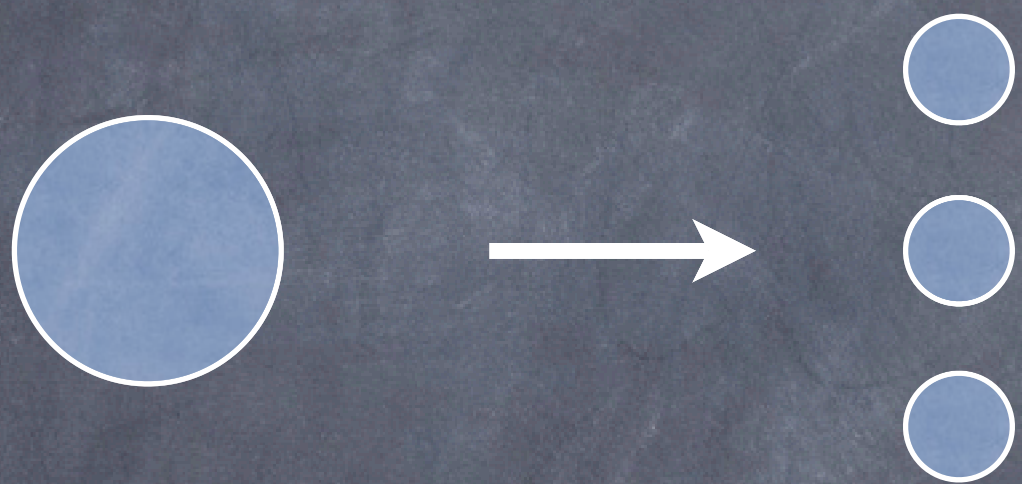
Spin 0	Higgs (H)	Spin 1/2	Higgsino ($\tilde{H}$)
Spin 1/2	Quark (Q), Lepton (L)	Spin 0	Squark ($\tilde{Q}$), Slepton ($\tilde{L}$)
Spin 1	γ, G, W, Z	Spin 1/2	$\tilde{\gamma}$, $\tilde{G}$, $\tilde{W}$, $\tilde{Z}$

[SM particles] [Superpartners]

[R_p=even] [R_p=odd]

LSP dark matter

Lightest superpartner (LSP) is absolutely stable under R-parity.



SM particle (R_p=even)

SM particle (R_p=even)

. . .

LSP (R_p=odd)

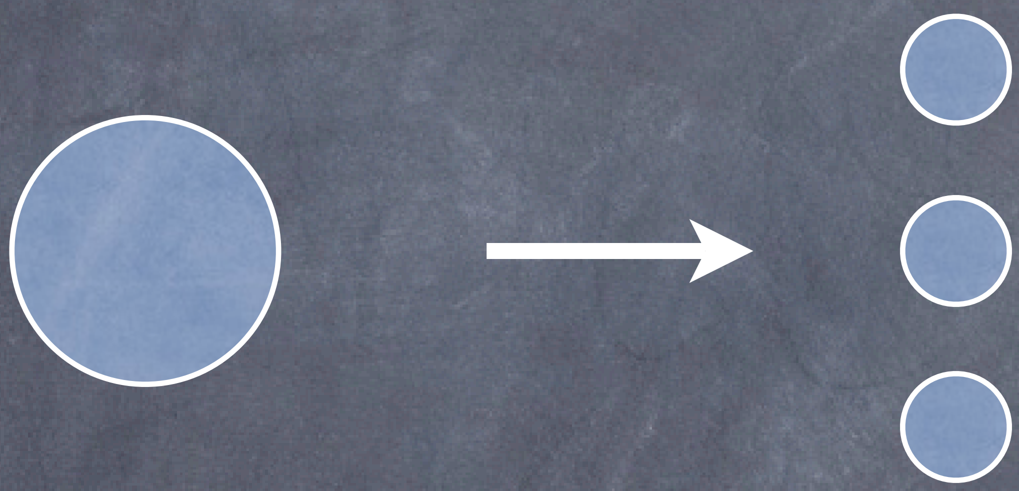
[Total R_p=odd]

[Total R_p=even]

Neutralino is a good DM candidate if it is LSP.

LSP dark matter

Lightest superpartner (LSP) is absolutely stable under R-parity.



SM particle (R_p=even)

SM particle (R_p=even)

. . .

LSP (R_p=odd)

[Total R_p=odd]

[Total

Most popular DM candidate

Neutralino is a good DM candidate if it is LSP.

SUSY with R-parity

$$
\begin{aligned}
W &= \mu H_u H_d \\
&+ y_E H_d L E^c + y_D H_d Q D^c + y_U H_u Q U^c \\
&+ \cancel{\lambda L L E^c + \lambda' L Q D^c + \mu' L H_u + \lambda'' U^c D^c D^c} \\
&+ \frac{\eta_1}{\Lambda} Q Q Q L + \frac{\eta_2}{\Lambda} U^c U^c D^c E^c + \cdots
\end{aligned}
$$

- over-constraining of R-parity: All renormalizable L violating and B violating terms are (unnecessarily) forbidden.
- under-constraining of R-parity: Dim 5 L&B violating terms still mediate too fast proton decay. Weinberg [1982]

Look for an alternative

R-parity may be still valid, but possibilities are limited.
(ex) What if B/L violating signals are found?

Find an alternative SUSY companion symmetry, which can

- allow B or L violating terms
- address proton stability (including non-renormalizable operators)
- address dark matter issue (non-LSP dark matter)

4. TeV scale U(1)′ gauge symmetry

4. TeV scale U(1)′ gauge symmetry

alternative to R-parity
for p&DM stability

Our model

HL, Luhn, Matchev [2007~2008]

$$U(1)' \to Z_6 = B_3 \times U_2$$

B_3 (Baryon triality): stabilizes proton

U_2 (U-parity): stabilizes hidden sector DM candidate

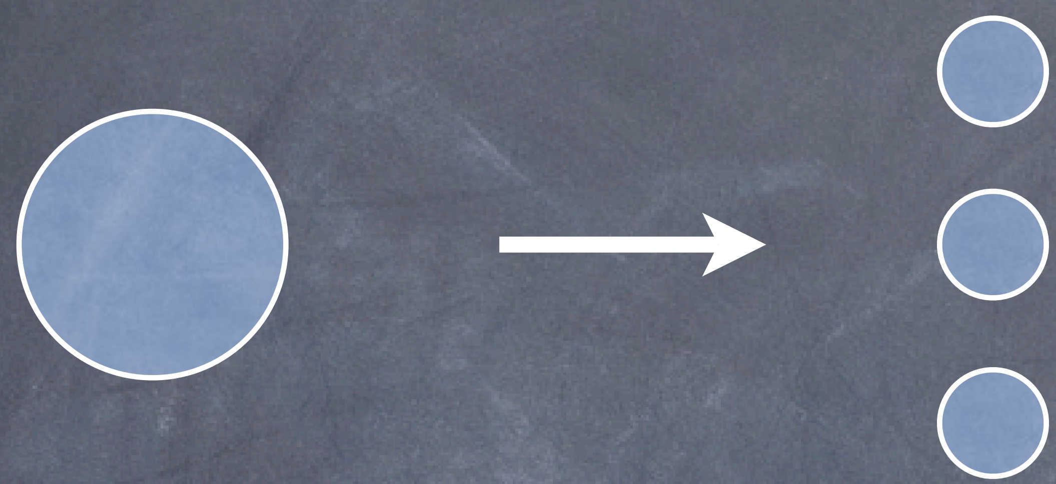
B_3 (Baryon triality)

Ibanez, Ross [1992]

	Q	U^c	D^c	L	E^c	N^c	H_u	H_d	meaning
B_3	0	-1	1	-1	-1	0	1	-1	$-B+y/3$

- B_3 selection rule: $\Delta B = 3 \times \text{integer}$
  - L is freely violated.
  - B can be violated only by $3 \times$integer.

Stable proton under B_3



pion ($B=0$)

electron ($B=0$)

. . .

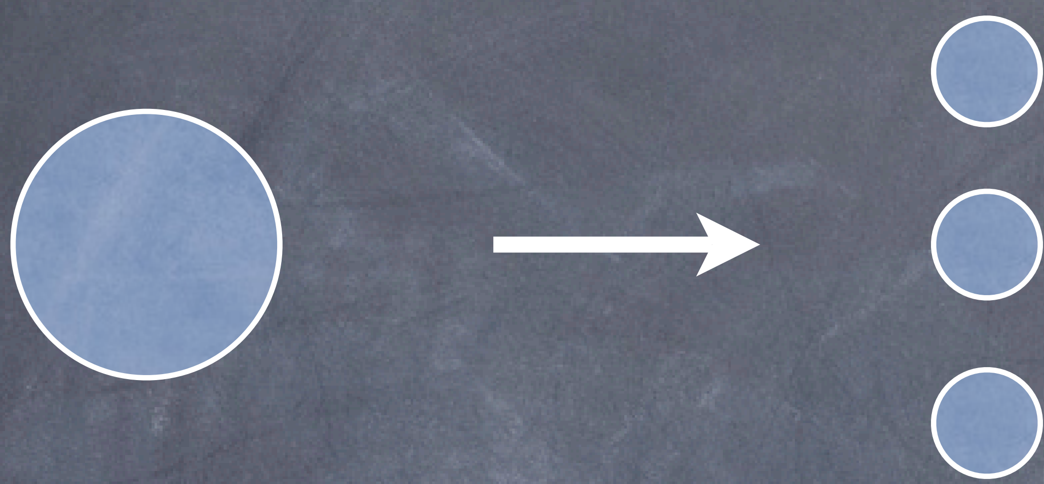
proton ($B=1$)

lightest baryon
[Total $B=1$]

non-baryons
[Total $B=0$]

Proton decay ($\Delta B=1$) is forbidden by B_3 ($\Delta B=3\times$integer).

Stable proton under B_3



pion (B=0)

electron (B=0)

. . .

proton (B=1)

lightest baryon
[Total B=1]

non-baryons
[Total B=0]

Proton decay ($\Delta B=1$) is forbidden by B_3 ($\Delta B=3\times$integer).

Proton stability better than R-parity

U-parity (hidden sector parity)

Hur, HL, Nasri [2007]

Consider hidden sector fields (SM singlets), which interact only with U(1)′.

$$W_{hid} = SXX$$

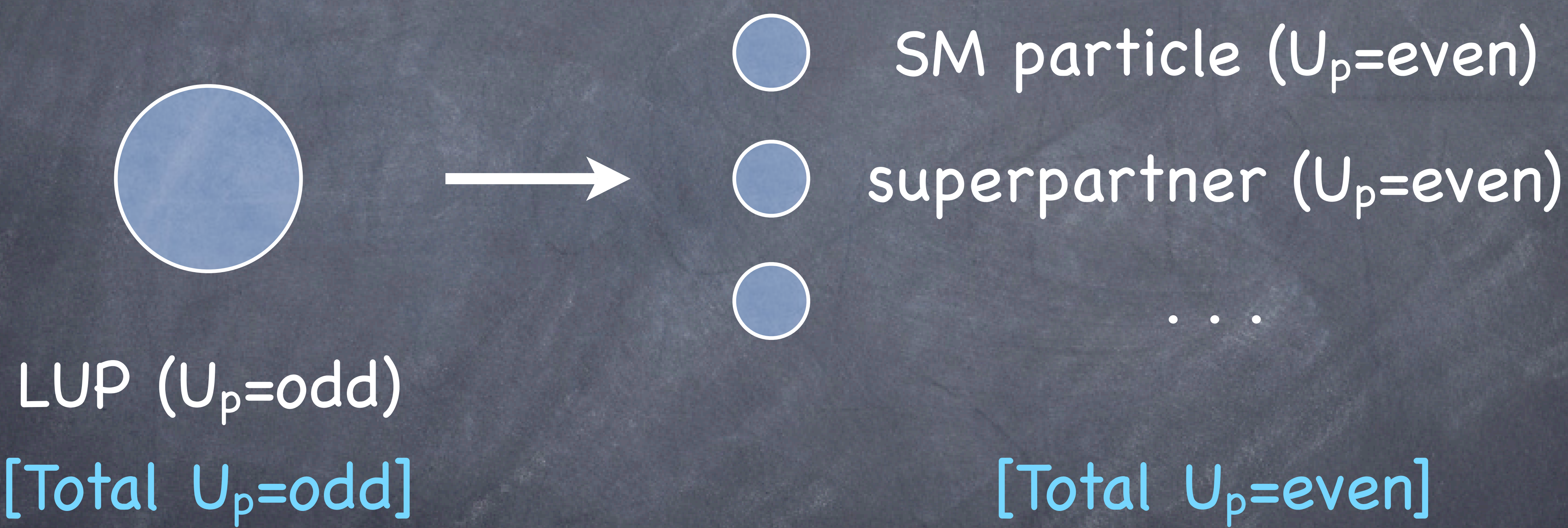
Higgs (H)	Higgsino ($\tilde{H}$)	
Quark (Q), Lepton (L)	Squark ($\tilde{Q}$), Slepton ($\tilde{L}$)	X, $\tilde{X}$
γ, G, W, Z	$\tilde{\gamma}$, $\tilde{G}$, $\tilde{W}$, $\tilde{Z}$	

[SM particles] [Superpartners] [Hidden sector]

[U_p=even] [U_p=odd]

LUP dark matter (hidden sector DM)

Lightest U-parity odd particle (LUP)
, hidden sector particle, is absolutely stable under U-parity.



LUP is a good DM candidate.

LUP dark matter (hidden sector DM)

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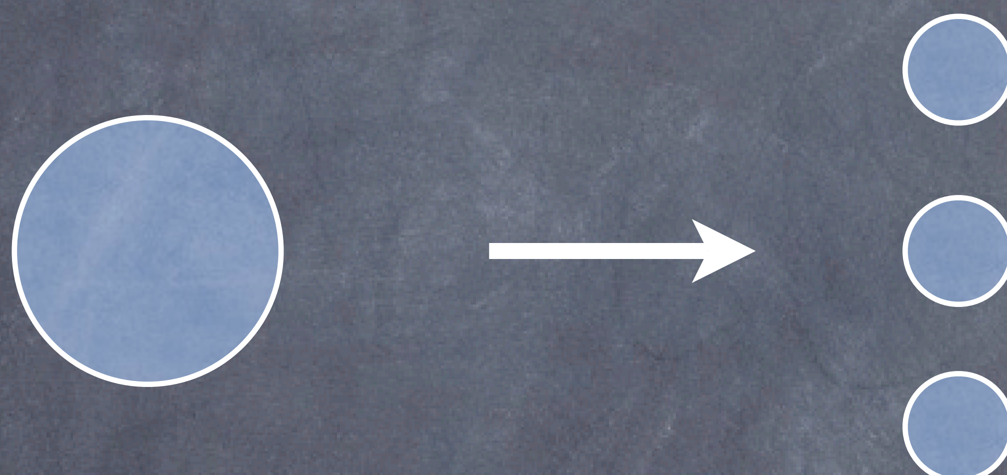


SM particle (U_p=even)

superpartner (U_p=even)

. . .

LUP (U_p=odd)

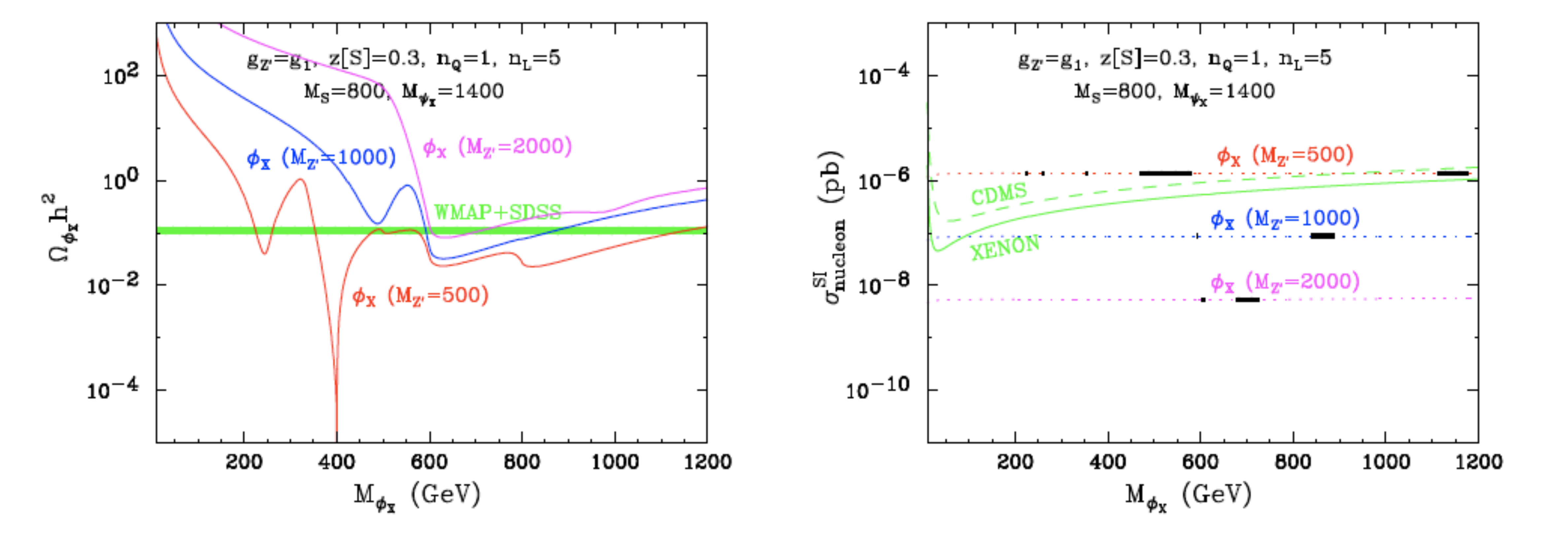
[Total U_p=odd]

[Tot

Similar to LSP DM under R-parity

LUP is a good DM candidate.

What about relic density and direct detection constraints?



[Relic density] [Direct detection]

LUP is a viable dark matter candidate.

Recap: R-parity vs. U(1)′ in SUSY

	R-parity	U(1)′ -> $B_3 \times U_2$
proton	stable (for renormalizable terms)	stable (B_3)
dark matter	stable LSP	stable LUP (U_2)

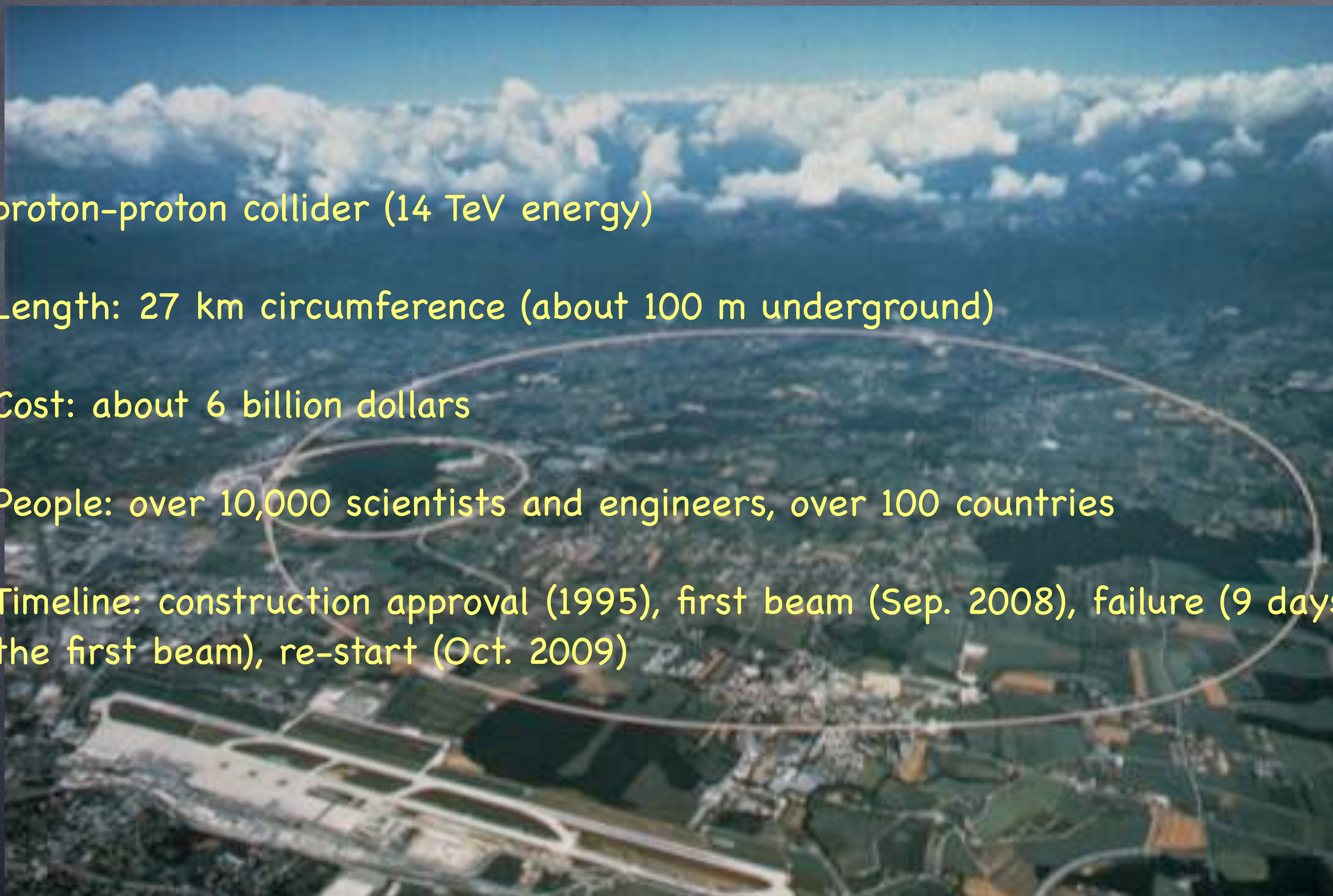
- TeV scale U(1)′ is a viable alternative to R-parity for stability of proton and dark matter.

Same SUSY, but different SUSY companion symmetries
-> Distinguishable LHC predictions

5. LHC implications

of TeV scale U(1)′

Large Hadron Collider (LHC)
in Geneva, Switzerland

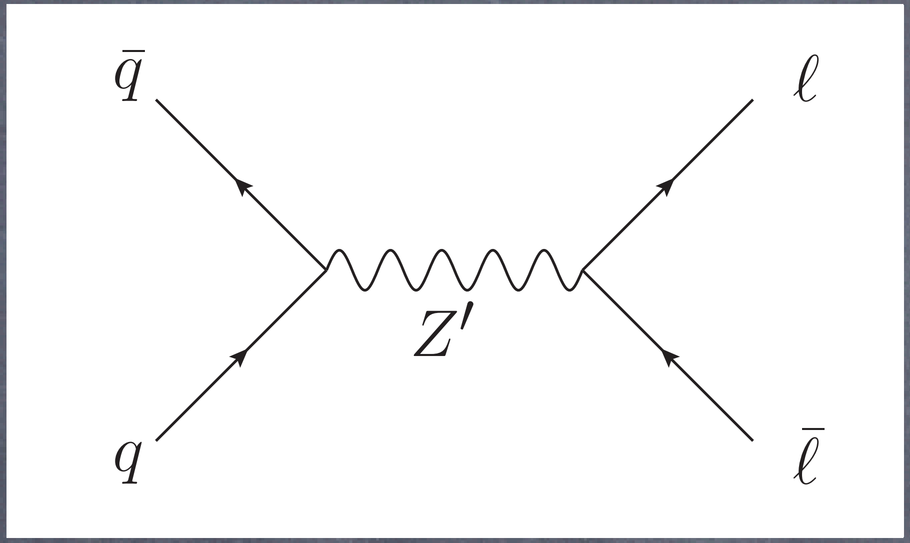


- proton-proton collider (14 TeV energy)
- Length: 27 km circumference (about 100 m underground)
- Cost: about 6 billion dollars
- People: over 10,000 scientists and engineers, over 100 countries
- Timeline: construction approval (1995), first beam (Sep. 2008), failure (9 days after the first beam), re-start (Oct. 2009)

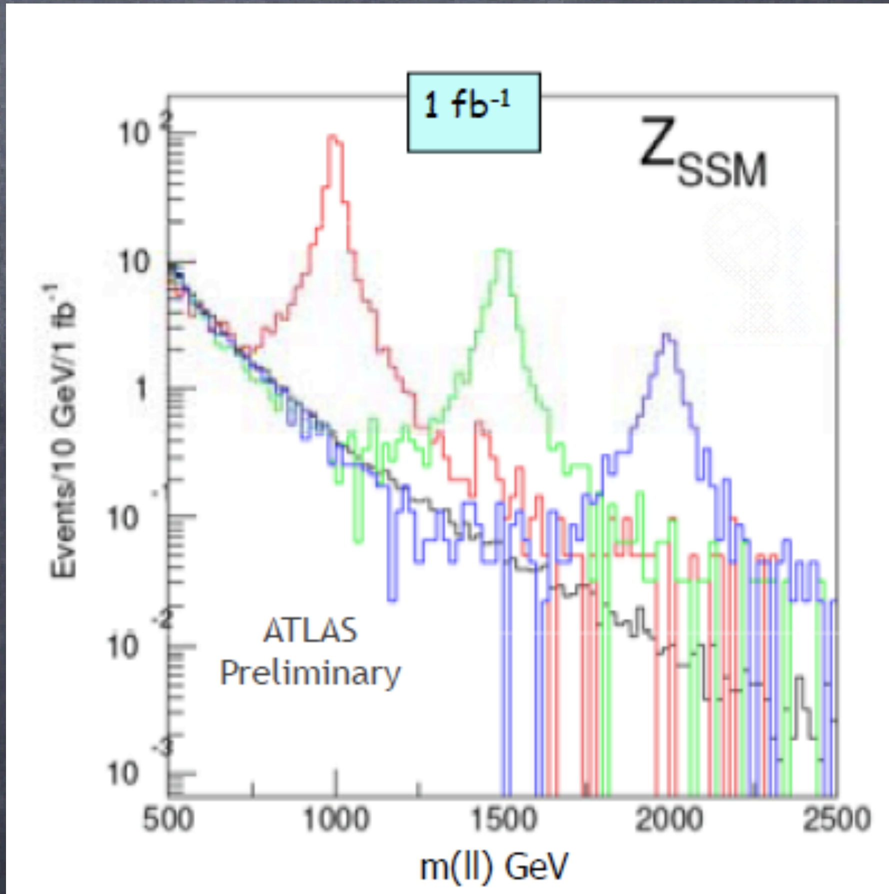
TeV scale Z′ gauge boson

Motivation order: Higgs -> SUSY -> TeV scale U(1)′

TeV scale Z′

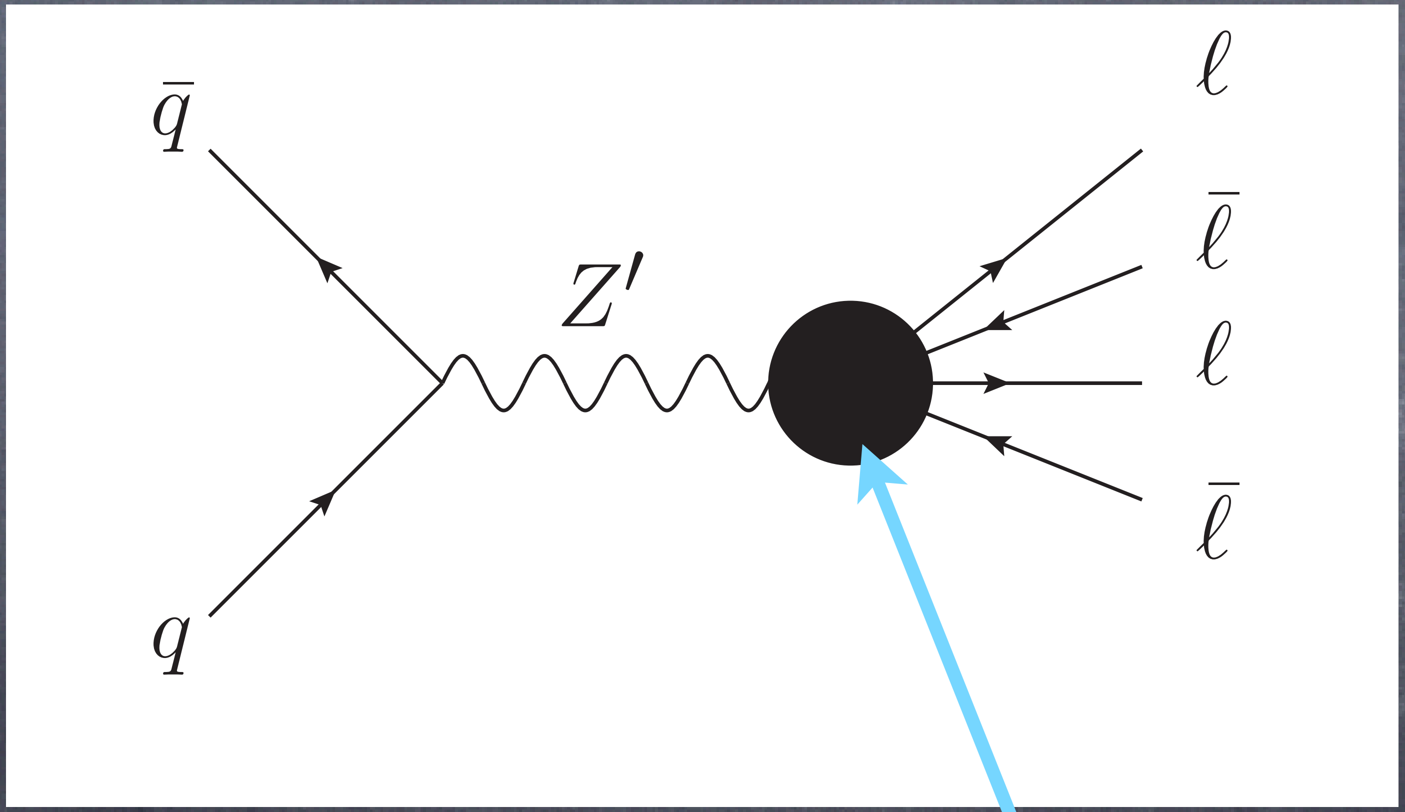


Dilepton Z′ resonance is very likely first discovery at LHC because of
(i) enhanced cross section
(ii) clean leptonic signal



Our approach for LHC

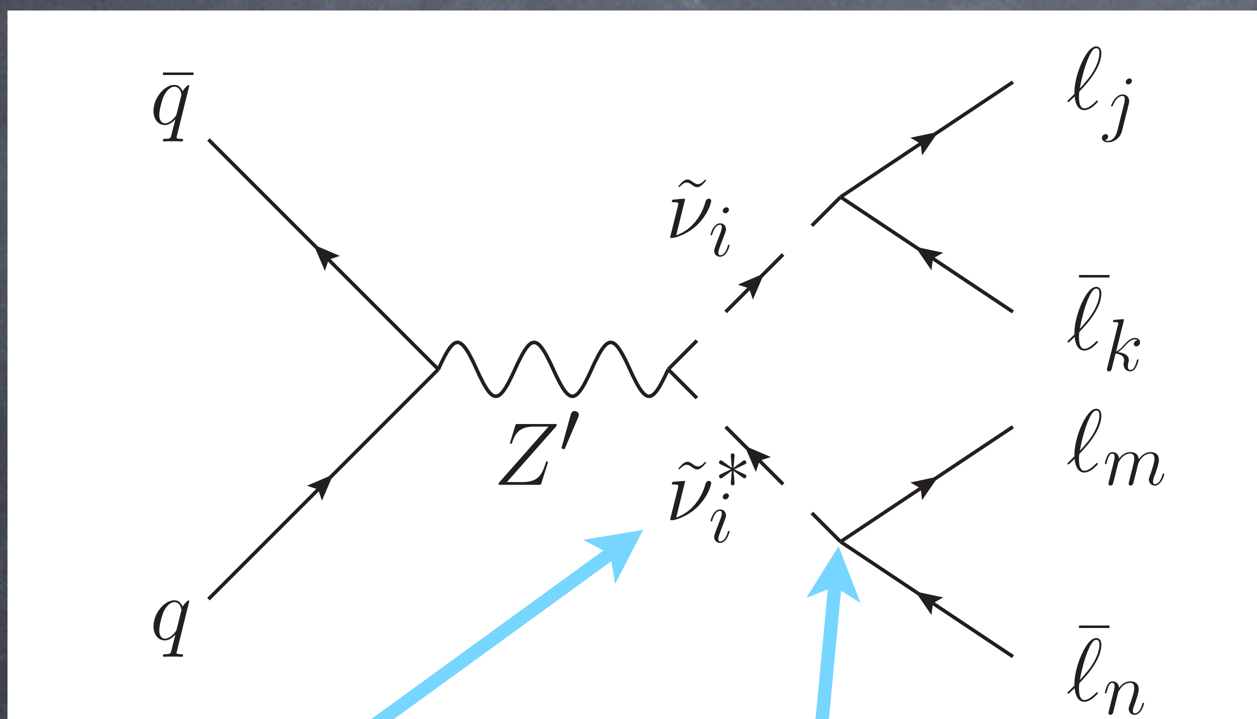
Use various leptonic Z′ resonances
for new physics search.

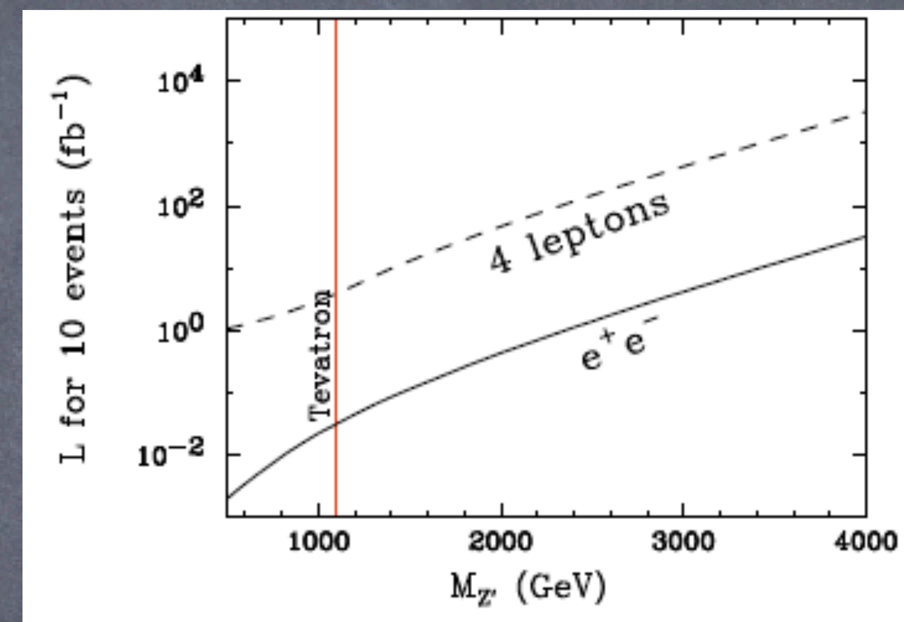


new particle
(superpartner, Higgs)
in the middle

4 lepton resonance at Z′
: SUSY search (for sneutrino LSP case)

HL [2008]





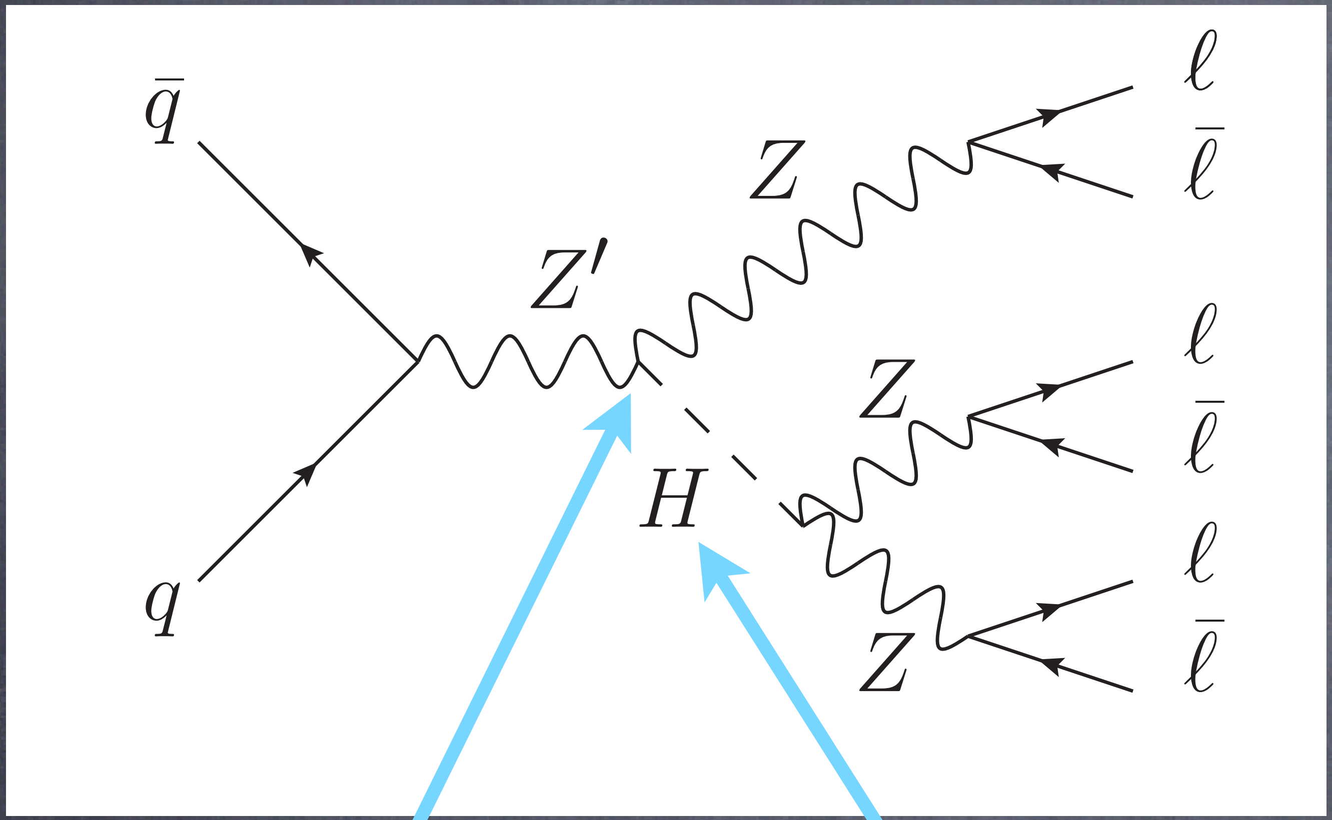
superpartner
(sneutrino)

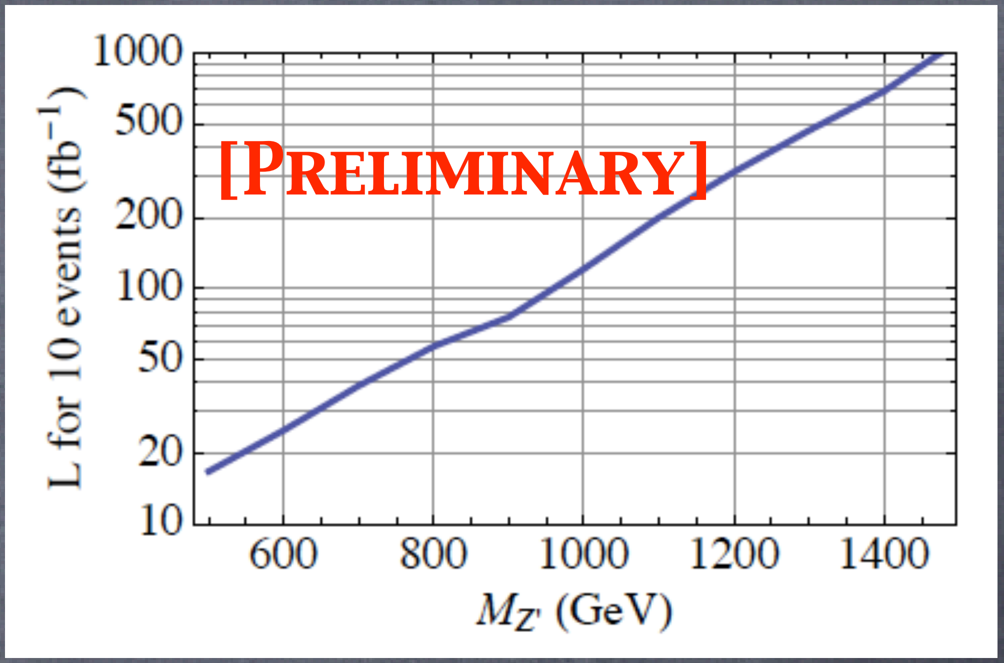
(ex) L=13 fb^{-1} for $M_{Z'}$=1500 GeV
[Details omitted]

R-parity violating coupling (λLLE^c)
(Scalar neutrino LSP decays to SM particles)

6 lepton resonance at Z′
: Higgs search (regardless of SUSY)

[in preparation]





Higgs

(ex) L=40 fb^{-1} for $M_{Z'}$=700 GeV
[Details omitted]

Z′-Z-H coupling can be sizable if Higgs has U(1)′ charge.
(longitudinal mode of Z is imaginary part of H)

Summary

1. Motivation

Higgs -> SUSY -> U(1)′

2. TeV scale U(1)′ is a good SUSY companion symmetry (to stabilize proton and dark matter) alternative to R_p.

3. LHC implications (various leptonic resonances)

2L resonance at $M_{Z'}$: Z′ search

4L resonance at $M_{Z'}$: SUSY search

6L resonance at $M_{Z'}$: Higgs search

TeV scale Z′ is well-motivated, and it can help searching for major discovery goals (Higgs, SUSY) at LHC.